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Long-Term Effects of Poultry Litter, Alum-Treated Litter, and Ammonium Nitrate on Aluminum Availability in Soils

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ABSTRACT

Research has shown that alum [$Al_2(SO_4)_3 \cdot 14H_2O$] applications to poultry litter can greatly reduce phosphorus (P) runoff, as well as decrease ammonia (NH_3) volatilization. However, the long-term effects of fertilizing with alum-treated litter are unknown. The objectives of this study were to evaluate the long-term effects of normal poultry litter, alum-treated litter, and ammonium nitrate (NH_4NO_3) on aluminum (Al) availability in soils, Al uptake by tall fescue (*Festuca arundinacea* Schreb.), and tall fescue yields. A long-term study was initiated in April of 1995. There were 13 treatments (unfertilized control, four rates of normal litter, four rates of alum-treated litter, and four rates of NH_4NO_3) in a randomized block design. All fertilizers were broadcast applied to 52 small plots (3.05×1.52 m) cropped to tall fescue annually in the spring. Litter application rates were 2.24, 4.49, 6.73, and 8.98 Mg ha^{-1} (1, 2, 3, and 4 tons acre^{-1}); NH_4NO_3 rates were 65, 130, 195, and 260 kg N ha^{-1} and were based on the amount of N applied with alum-treated litter. Soil pH, exchangeable Al (extracted with potassium chloride), Al uptake by fescue, and fescue yields were monitored periodically over time. Ammonium nitrate applications resulted in reductions in soil pH beginning in Year 3, causing exchangeable Al values to increase from less than 1 mg Al kg^{-1} soil in Year 2 to over 100 mg Al kg^{-1} soil in Year 7 for many of the NH_4NO_3 plots. In contrast, normal and alum-treated litter resulted in an increase in soil pH, which decreased exchangeable Al when compared to unfertilized controls. Severe yield reductions were observed with NH_4NO_3 beginning in Year 6, which were due to high levels of acidity and exchangeable Al. Aluminum uptake by forage and Al runoff from the plots were not affected by treatment. Fescue yields were highest with alum-treated litter (annual average = 7.36 Mg ha^{-1}), followed by normal litter (6.93 Mg ha^{-1}), NH_4NO_3 (6.16 Mg ha^{-1}), and the control (2.89 Mg ha^{-1}). These data indicate that poultry litter, particularly alum-treated litter, may be a more sustainable fertilizer than NH_4NO_3.

Phosphorus runoff from fields fertilized with animal manures, such as poultry litter, can have a negative impact on water quality in many regions of the United States. In northwestern Arkansas and northeastern Oklahoma there are several river systems, including the Eucha/Spavinaw Watershed and the Illinois River Watershed, which are experiencing water quality problems due to excessive P pollution from both point and nonpoint sources. The Eucha/Spavinaw Watershed serves as the drinking water source for the city of Tulsa, OK. In recent years algal blooms on Lakes Eucha and Spavinaw have resulted in high levels of geosmin, a metabolite produced by certain algae that causes taste and odor problems in drinking water. The threshold odor concentration for geosmin in drinking water is 10 ng L^{-1} (Izaguirre et al., 1982). Phosphorus is generally the limiting element for eutrophication in freshwater bodies, such as rivers, lakes, and reservoirs (Schindler, 1977). As a result of these problems, the city of Tulsa sued eight major poultry companies located in Arkansas. As part of the settlement, the companies paid millions of dollars to the city of Tulsa.

Arkansas is one of the nation's leading poultry producing states, with over one billion (10^9) broilers produced annually. Poultry and livestock are extremely important to the economy of Arkansas, contributing an estimated $7 to 8 billion annually. However, in addition to the economic benefits of this industry there may be threats to the environment. Edwards and Daniel (1992a, 1992b) documented high P concentrations in runoff water from pastures fertilized with litter, even at rates considered low to moderate. The majority (>80%) of the P in runoff water from pastures fertilized with poultry litter is dissolved P, which is the form most readily available to algae (Edwards and Daniel, 1993; Sonzogni et al., 1982). Based on this finding, Moore and Miller (1994) hypothesized that P runoff from pastures fertilized with litter could be decreased by reducing soluble P levels in litter using chemical amendments to precipitate P. They demonstrated that soluble P levels could be reduced by up to 99% with various Al, Ca, and Fe amendments. This work has been validated by several researchers, who showed aluminum sulfate (alum) greatly reduces soluble P in litter (Moore et al., 1995a, 1995b, 1996, 1999, 2000; Miles et al., 2003; Sims and Luka-McCafferty, 2002). Shreve et al. (1995) showed that P runoff from fescue plots fertilized with alum-treated litter was 87% lower than from plots fertilized with untreated litter. The tall fescue fertilized with alum-treated litter in the study by Shreve et al. (1995) also had significantly higher yields than fescue fertilized with normal litter, due to increased N availability. Subsequent studies showed that alum applications to litter greatly reduce ammonia (NH_3) volatilization, improving the fertilizer value of the litter (Moore et al., 1995a, 1996, 2000).

Ammonia volatilization from poultry litter in poultry rearing facilities results in high levels of NH_3 in the atmosphere of these facilities, which is detrimental to the health of the birds and to farm workers. The critical level of atmospheric NH_3 for poultry is 25 μL L^{-1} (Carlile, 1984). Above this concentration, NH_3 can cause reduced growth rates, reduced egg production, poor feed effi-

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ciency, damage to the respiratory tract, immunosuppression, and retinal damage (Carlile, 1984).

Because of the negative effects that NH_3 has on poultry performance, many different chemical amendments have been tested in the past to reduce NH_3 volatilization from poultry litter. Moore et al. (1995a, 1996) found that alum and phosphoric acid were the most effective compounds that could be used for this purpose. Later work by Moore et al. (1999, 2000) showed that when alum applications were made to litter in commercial broiler farms poultry performance was greatly enhanced. Moore et al. (2000) showed that broilers grown in houses treated with alum were heavier and had better feed conversion and lower mortality than birds grown in untreated houses. Energy use was also lower in alum-treated houses, due to lower ventilation requirements in the winter. Line (2002) has also shown that the use of alum greatly reduces the number of pathogens, such as *Campylobacter* and *Salmonella*, both in poultry litter and on bird carcasses. As a result of these production benefits, over 600 million chickens are grown annually in the United States with alum.

These improvements in poultry performance make alum treatment of poultry litter one of the few cost-effective best management practices that both reduces pollution and increases agricultural productivity. However, questions have arisen regarding the impact of adding Al containing compounds like alum to poultry litter. Moore et al. (1998) showed that heavy metal (arsenic, copper, and zinc) concentrations in runoff from alum-treated poultry litter were significantly lower than that from normal litter. Likewise, Nichols et al. (1997) found that the addition of alum to poultry litter caused a 40% reduction in β-17 estradiol (estrogen) runoff compared to normal litter. The addition of alum has no effect on poultry litter decomposition in soils, except for the possible increased release of N during mineralization (Gilmour et al., 2004), which would benefit crop production. Studies conducted on small watersheds showed that the addition of alum reduces P runoff by at least 75% at the field scale (Moore et al., 1999, 2000). As a result of these environmental benefits, the USDA-NRCS has made the use of alum a conservation practice standard in several states (Arkansas, Alabama, Tennessee, and South Carolina).

The objectives of this study were to evaluate the long-term effects of three sources of nitrogen (normal poultry litter, alum-treated litter, and NH_4NO_3) on Al availability in soils, Al runoff, Al uptake by tall fescue, and tall fescue yields.

MATERIALS AND METHODS

A long-term (20 yr) study was initiated in April of 1995 using 52 small plots (1.52 × 3.05 m, with 5% slope) located at the Main Agricultural Experiment Station of the University of Arkansas on a Captina silt loam soil (fine-silty, siliceous, mesic Typic Fragiudult). The plots are equipped with runoff collection troughs at the downslope end which enables the collection of runoff water and have metal borders (15 cm tall of which 10 cm is buried) on the remaining three sides to hydrologically isolate the plots. There were a total of 13 treatments: four rates of alum-treated poultry litter, four rates of untreated poultry litter, four rates of NH_4NO_3, and one unfertilized control. Litter application rates were 2.24, 4.49, 6.73, and 8.98 Mg ha^{-1} (1, 2, 3, and 4 tons acre^{-1}). Ammonium nitrate application rates were 65, 130, 195, and 260 kg N ha^{-1}, and were based on the amount of total N added with the four rates of alum-treated litter during Year 1. There were four replications per treatment in a randomized block design.

Soil samples (0–5 cm) were taken from each of the 52 plots (10 cores per plot) before the study and analyzed for Mehlich-III P and water-soluble P (Self-Davis et al., 2000). The 13 fertilizer treatments were then randomized, based on Mehlich-III P values, so that the average soil test P level for each treatment at the beginning of the study was within 1 mg P kg^{-1} of the overall average of all 52 plots (131 mg P kg^{-1}).

Soil samples (0–5 cm) were also taken periodically (at least one time per year) for the duration of the study and analyzed for Mehlich-III P (Mehlich, 1984), water-soluble P (Self-Davis et al., 2000), soil pH in KCl, exchangeable Al, and titratable acidity. The holes formed by soil sampling where plugged with cores taken from the border area adjacent to each plot. Soil pH in water was also measured; however, the reproducibility was poor, so KCl pH was used. For KCl pH, exchangeable Al, and titratable acidity, 7 g soil were shaken with 70 mL of 1 *M* KCl for 1 h, centrifuged at 6000 rpm, and filtered through 0.45-μm filters. Exchangeable Al samples were acidified to pH 2.0 with HCl; Al was then analyzed using a Spectro Model D ICP (Spectro Analytical Instruments, Fitchburg, MA). Titratable acidity was determined by titrating a 20-mL aliquot to pH 7.0 using 0.0005 *M* NaOH.

In April 2002, after 7 yr of applications, four soil cores were taken from each plot at the following depths: 0 to 5, 5 to 10, 10 to 20, 20 to 30, 30 to 40, and 40 to 50 cm. These samples were analyzed for exchangeable Al, pH, Mehlich-III P, and nitric and perchloric acid–extractable Al. Aluminum was analyzed using inductively coupled plasma (ICP) after digestion with a mixture of nitric and perchloric acid.

The poultry litter used for this study was obtained from six commercial broiler houses located in northwestern Arkansas which had been part of a study on the effects of alum on NH_3 volatilization and poultry production (Moore et al., 1999, 2000). Alum had been applied to three of the houses at a rate of 1816 kg $Al_2(SO_4)_3{\cdot}14H_2O$ house^{-1} after each growout (except the final growout of each year) since 1994 and mixed into the litter using a litter "de-caker." This rate is equivalent to 1.22 kg alum m^{-2} or 0.091 kg alum bird^{-1}. Chemical characteristics of the untreated and alum-treated litter used in this study for Year 1 are given in Table 1. Although the nutrient content varied slightly from year to year, these values are representative of litter used throughout the study.

To measure nutrient content and yields of tall fescue, a 1-m^2 area of each plot was periodically cut to a height of 10 cm with a bagger mower. During Year 6 of the study, problems emerged with moles burrowing through the plots. During this time, some soil contamination of the plant tissue was observed via the presence of large amounts of titanium in the plant samples (Cherney and Robinson, 1983). To avoid soil contamination, subsamples for nutrient analysis were clipped by hand thereafter. For total metal analysis of plant tissue, 0.5 g of dried, ground plant material was digested in nitric acid and analyzed using ICP.

To evaluate Al runoff from the plots, a rainfall simulation was conducted during Year 6 (5 Nov. 2001) using standard rainfall simulators (Edwards et al., 1992) to provide a 50 mm h^{-1} precipitation event. This event was approximately six months after fertilization. Rainfall was simulated for a sufficient duration to allow 30 min of continuous runoff from each plot.

Table 1. Chemical characteristics of poultry litter used in Year 1. Data are from Moore et al. (1998).

	Alum-treated litter		Untreated litter	
Parameter	Average	SD	Average	SD
pH	7.59	0.77	8.04	0.18
EC†, μS cm^{-1}	10 833	471	6611	311
Total elements, g kg^{-1}				
N	38.5	1.1	34.5	2.7
S	33.9	9.8	6.8	0.4
Ca	29.4	3.6	34.1	4.2
K	27.4	2.7	26.4	1.6
P	18.9	1.8	22.4	1.7
Al	18.7	6.0	1.18	0.2
Na	7.54	0.6	7.84	0.6
Mg	5.79	0.7	6.57	0.4
Total elements, mg kg^{-1}				
Fe	1 717	310	1095	155
Mn	893	216	956	134
Cu	679	93	748	102
Zn	598	51	718	69
B	46	4	51	4
Ti	31	11	44	19
As	20	8	43	4
Ni	21	5	15	2
Pb	8	2	11	2
Co	6	2	6	1
Mo	5	0.5	6	0.5
Cd	3	0.4	3	0.2

† Electrical conductivity.

Runoff samples were collected during each event at 2.5, 7.5, 12.5, 17.5, 22.5, and 27.5 min after continuous runoff was observed. Runoff samples were collected in 1-L plastic containers. Time to runoff was recorded for each plot and collection time and volume of runoff per unit time were recorded for each runoff sample. Time to runoff varied from plot to plot, but generally occurred within 15 min. The six water samples from each plot were composited into one sample, based on runoff volumes on a flow-weighted basis. A portion of each runoff water sample was filtered through a 0.45-μm membrane and acidified to pH 2 with concentrated HCl for soluble Al analysis using ICP. Total Al was analyzed on unfiltered samples with ICP after digestion with nitric acid according to APHA Method 3030E (American Public Health Association, 1992).

Statistical analysis of the data were performed using SAS (SAS Institute, 1985). Significant differences between means were evaluated using Fisher's Protected LSD with α set at 0.05.

RESULTS AND DISCUSSION

Poultry Litter Total Metal Contents

Chemical characteristics of the alum-treated litter were similar to normal litter, except for total Al and S, which were higher in the alum-treated litter (Table 1). Higher Al and S would be expected with the addition of alum. Compared to untreated litter, the alum-treated litter had a slightly higher N content (38.5 vs. 34.5 g kg^{-1}), a lower pH (7.6 vs. 8.0), and a higher EC (10 833 vs. 6611 μS cm^{-1}). Higher N in the alum-treated litter is the result of less ammonia loss (Moore et al., 1995a, 1996).

Long-Term Effects on Soil Acidity and Aluminum

Soil pH

The average soil pH for the plots treated with the three fertilizer types and the unfertilized control is shown in

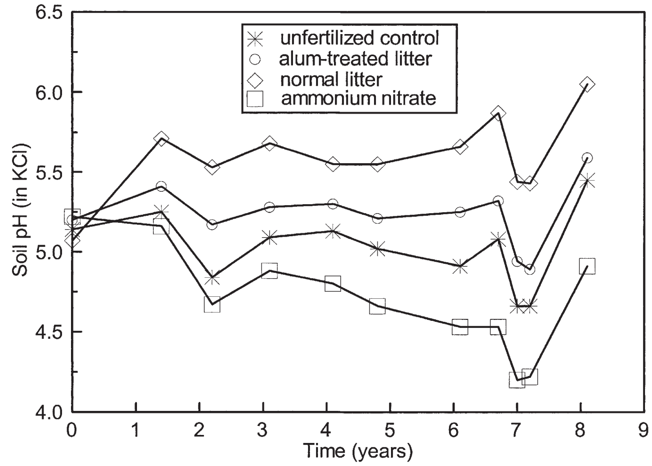

Fig. 1. Temporal variability in soil pH as a function of fertilizer type (values represent averages of the four rates). Samples taken from the 0- to 5-cm depth.

Fig. 1 (n = 4 for each point representing a control; n = 16 for the other treatments). The pH of the soil at the beginning of the experiment ranged from 5.1 to 5.2. Soil pH increased with the addition of alum-treated and normal litter, with the latter resulting in higher pH values. The pH after 7 yr for all the different treatments is shown in Fig. 2. Normal litter had the greatest liming effect, with increasing rates resulting in higher pH values. The highest rate of normal litter resulted in a pH of 5.8 at Year 7. The pH of soil fertilized with alum-treated litter at all rates was significantly higher than the unfertilized control; however, differences in pH between the various rates of alum were not significantly different. Applications of NH_4NO_3 resulted in a linear decrease in soil pH as a function of application rate, with the highest rate resulting in a pH of 3.9 at Year 7 (Fig. 2).

It has long been known that commercial ammoniacal fertilizers, like NH_4NO_3, cause soil acidity problems. Pierre (1928) showed that this was particularly true for the highly leached, weakly buffered soils of the southeastern portion of the United States. According to Adams (1984), the work of Pierre (1928) was instrumental in causing great concern in this country for the effects "acid-forming" commercial N fertilizers have on soil pH and crop yields. The acidity is created by nitrification of ammonium, as follows:

$$NH_4NO_3 + 2O_2 \rightarrow 2NO_3^- + 2H^+ + H_2O \quad [1]$$

From this reaction, one would predict that 28 g of NH_4NO_3 would produce acidity equivalent to 100 g of $CaCO_3$. However, Pierre (1928) showed that this was not the case; the amount of acidity was actually lower. He explained these results using the concept of physiological acidity and basicity, which results when plants take up different amounts of cations and anions (the uptake of nitrate in excess of cations will lower the acidity by leaving more bases in the soil).

Although alum-treated and normal poultry litter contain large amounts of ammoniacal N, the soil pH increased with the addition of these materials (Fig. 1 and 2). The reason for this is that poultry manure contains

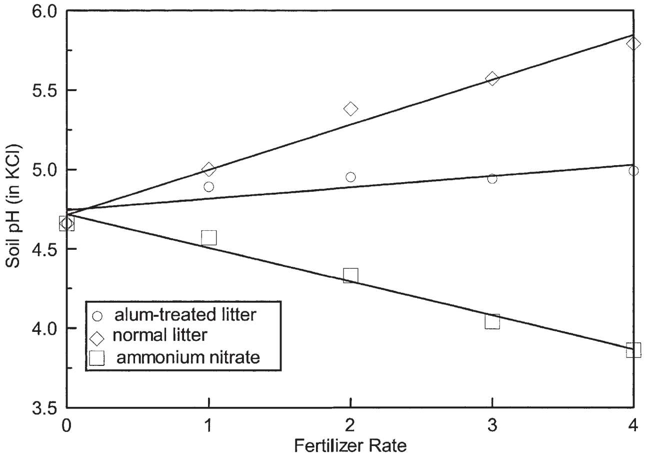

Fig. 2. Soil pH as a function of fertilizer treatment and rate after 7 yr ($LSD_{0.05}$ = 0.18). Samples taken from the 0- to 5-cm depth. Fertilizer rates (Rates 1, 2, 3, and 4) were respectively 2.24, 4.49, 6.73, and 8.98 Mg ha^{-1} for poultry litter and 65, 130, 195, and 260 kg N ha^{-1} for ammonium nitrate.

large amounts of bases, such as calcium carbonate, which originate from the diet of the birds. These bases neutralize the acidity produced by nitrification. When alum is first added to poultry litter, it produces acidity as follows:

$$Al_2(SO_4)_3{\cdot}14H_2O + 6H_2O \rightarrow 2Al(OH)_3 + 6H^+ + 3SO_4^{2-} + 14H_2O \quad [2]$$

This acidity initially reduces the litter pH in the poultry barn from around 8 to below 6 (Moore et al., 1999, 2000). This reduction in pH shifts the ammonia/ammonium equilibrium in the litter toward ammonium, as follows:

$$NH_3 + H^+ \rightarrow NH_4^+ \quad [3]$$

Since ammonium is not volatile, it builds up in the litter, causing alum-treated litter to have a higher N content than normal litter (Moore et al., 1995a). The pH of the litter increases as the birds add new manure to the old. The bases contained in the manure titrate the excess acidity from the alum. After about four weeks, the litter pH exceeds 7 and by the end of the flock, the pH of alum-treated litter is around 7.5 (Moore et al., 1999, 2000).

The main reason for this long-term study was to determine if the potential acidity (in the form of N) in alum-treated litter would exceed the base content of the litter, causing soil acidification. Clearly this was not the case, since all rates of alum-treated litter resulted in significantly higher soil pH values after 8 yr of fertilization than the unfertilized control plots. This shows that alum-treated litter does not cause soil acidification problems.

It is unclear why the pH of the plots decreased during Year 7. As mentioned earlier, there was a rainfall simulation on these plots in the fall of Year 6. The water used for this simulation was from the Fayetteville, AR, municipal supply which is derived from Beaver Lake. This water has Ca concentrations in excess of 50 mg L^{-1} and pH values of >7. Based on this chemistry one would predict that this water would have increased, rather than decreased, the pH of the soil at the surface.

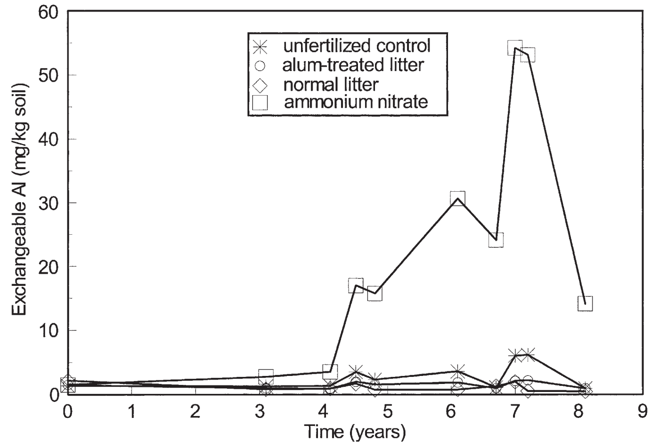

Fig. 3. Temporal variability in exchangeable Al as a function of fertilizer type (values represent averages of the four rates). Samples taken from the 0- to 5-cm depth.

Exchangeable Aluminum

Exchangeable Al values were below 3 mg Al kg^{-1} soil at the beginning of the study (Fig. 3). However, beginning in Year 3, the exchangeable Al values in the soils fertilized with NH_4NO_3 were significantly higher than the unfertilized controls. By Year 7, the average exchangeable Al in the NH_4NO_3 plots was in excess of 50 mg Al kg^{-1}, while in the unfertilized control it was 6 mg Al kg^{-1}. Exchangeable Al increased slightly in the unfertilized control plots during Years 4 to 7. In contrast, exchangeable Al levels in the soils fertilized with alum-treated and normal litter remained below 3 mg Al kg^{-1} and were not significantly different from each other.

The effect of fertilizer rate on exchangeable Al after 7 yr is shown in Fig. 4. These data indicate that as the rate of NH_4NO_3 increased, the exchangeable Al levels increased exponentially, whereas exchangeable Al decreased as a function of application rate in plots fertil-

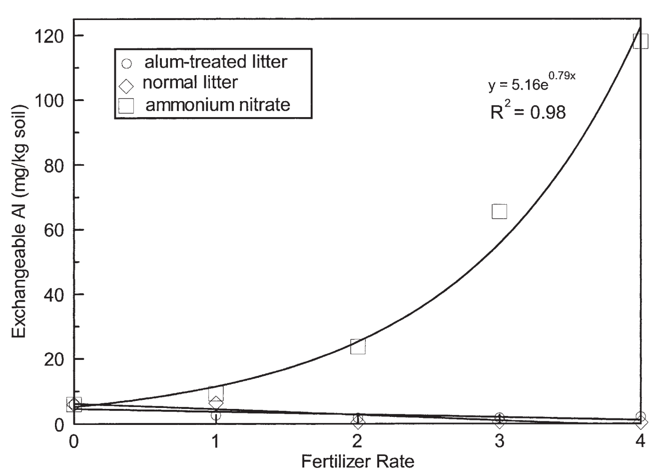

Fig. 4. Exchangeable Al as a function of fertilizer treatment and rate after 7 yr ($LSD_{0.05}$ = 15.1). Samples taken from the 0- to 5-cm depth. Fertilizer rates (Rates 1, 2, 3, and 4) were respectively 2.24, 4.49, 6.73, and 8.98 Mg ha^{-1} for poultry litter and 65, 130, 195, and 260 kg N ha^{-1} for ammonium nitrate.

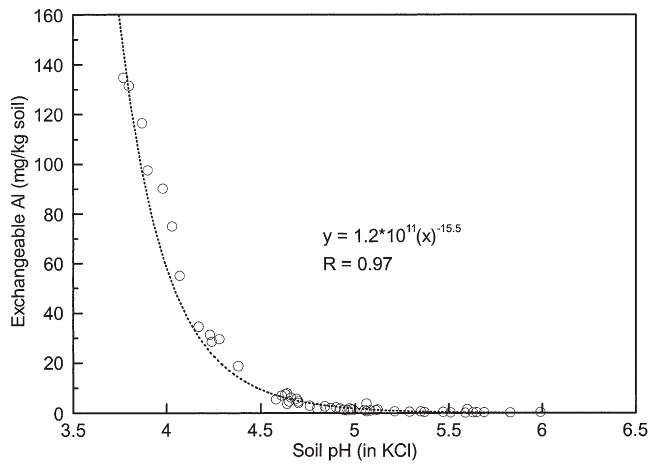

Fig. 5. Exchangeable Al as a function of soil pH. Samples taken from the 0- to 5-cm depth.

ized with alum-treated and normal litter. The highest rate of NH_4NO_3 resulted in exchangeable Al values of 118 mg Al kg^{-1}. Such extremely high levels of exchangeable Al, which is readily available in the soil, can have a negative effect on plant growth. The data in Fig. 4 also demonstrate how additions of either alum-treated or normal poultry litter reduce exchangeable Al, compared to the unfertilized control.

During the past few years some have questioned whether or not the use of alum-treated litter would lead to increased Al availability in soils (Sims and Luka-McCafferty, 2002). These data indicate that exchangeable Al values are lower in soils fertilized with alum-treated litter than unfertilized soil, with increasing rates of alum-treated litter resulting in lower available Al. The explanation for this behavior is simple: Al availability in soils is virtually independent of the total Al status, but rather is controlled by the geochemical conditions present. The main factor influencing Al availability in soils is pH, with acidic conditions resulting in the dissolution of clay minerals and Al oxides, causing high exchangeable Al. The relationship between exchangeable Al and soil pH during Year 7 from all 52 plots is shown in Fig. 5. These data illustrate the dependency of Al availability on soil pH.

Aluminum is the most abundant metal in most soils, which are comprised of alumino-silicate minerals. Total Al concentrations in soils vary from 1 to 30%, with an average of about 7% (Lindsay, 1979). Hence, in a typical soil the amount of Al contained in the upper 15 cm is roughly 156 800 kg ha^{-1} (140 000 lbs $acre^{-1}$). Alum-treated litter normally contains about 1% Al, assuming growers have used the highest recommended rate in the poultry house, as was done in this study. A typical litter application rate to pastures is 5.6 Mg ha^{-1} (2.5 tons $acre^{-1}$), which would result in the application of 56 kg Al ha^{-1} (50 lbs Al $acre^{-1}$). To increase the total soil Al level from 7 to 8% would take 22 400 kg Al ha^{-1} or 400 yr of annual applications of alum-treated litter at a rate of 5.6 Mg ha^{-1}. However, this would only affect the total Al; available Al would be expected to decrease, due to the increase in soil pH.

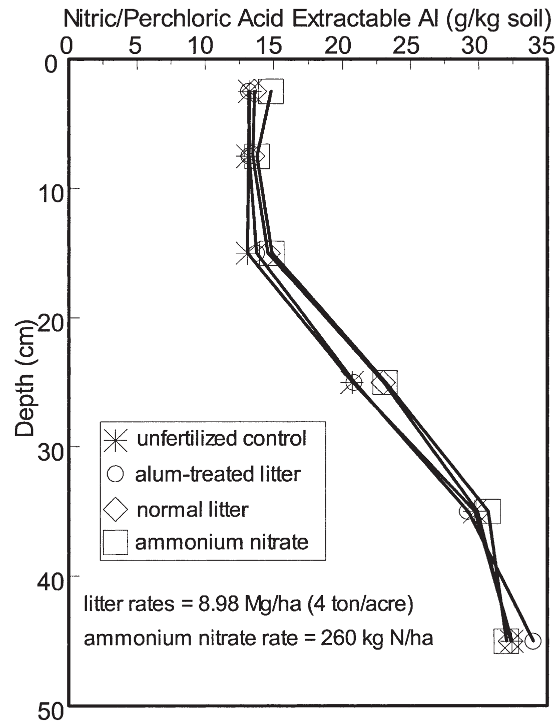

Fig. 6. Nitric and perchloric acid–extractable Al as a function of depth and fertilizer type at Year 7 ($LSD_{0.05}$ = 1.97).

Nitric and perchloric acid–extractable Al is plotted as a function of depth in Fig. 6. Although some researchers refer to this as "total Al" in soils, it is not. When standard soil samples were analyzed using this method, our recovery for other total metals, P, etc., was 100%. However, the recovery for Al was very poor (approximately 30%), indicating the results from this method cannot be referred to as total Al (data not shown). While this method does not digest all of the Al in soils, it would almost certainly digest the recently precipitated aluminum oxides or hydroxides or aluminum phosphates which would be the product of alum addition to litter. However, there was no significant difference in soil Al due to fertilizer type (Fig. 6). The data shown in Fig. 6 are for soils receiving the highest rate of litter (8.98 Mg ha^{-1}), hence these would have received the most Al.

As mentioned in Materials and Methods, titratable acidity was measured on KCl extracts by titrating 20 mL to pH 7. Exchangeable Al accounted for roughly 100% of the titratable acidity in the soil used for this study (Fig. 7), as indicated by the slope of 1.0 between these two parameters. These data indicate that very little exchangeable H^+ exists in these soils. According to Thomas and Hargrove (1984), exchangeable acidity in soils is almost always due entirely to monomeric Al^{3+}. This was first shown 100 yr ago by Veitch (1904) and has been substantiated over the years by many workers (Schofield, 1949; Thomas, 1960). However, some textbooks in soil science still incorrectly show that exchangeable H^+ makes a significant contribution to soil acidity, even in the pH range of this study.

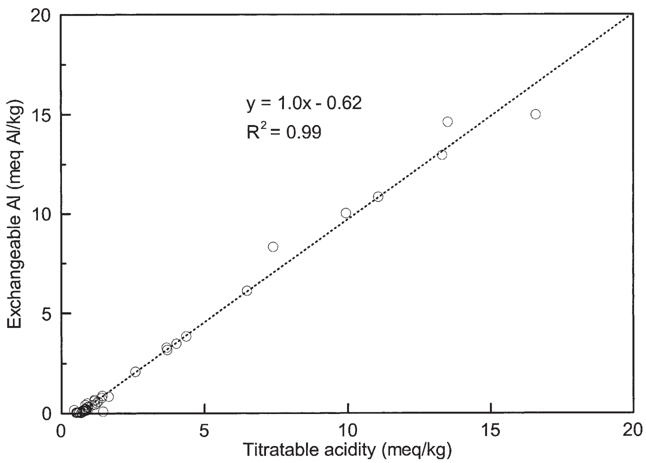

Fig. 7. Exchangeable Al as function of titratable acidity at Year 7. Samples taken from the 0- to 5-cm depth.

Aluminum Runoff

Total and soluble Al concentrations in runoff water from the rainfall simulation study conducted in the fall of Year 6 are shown in Fig. 8. Total Al concentrations in runoff water ranged from 0.6 to 1.6 mg Al L^{-1}. Soluble Al concentrations were between 0.1 and 0.2 mg Al L^{-1}. None of the treatments had a significant effect on total or soluble Al runoff. These results were somewhat surprising, since we had hypothesized that both total and soluble Al runoff would be higher with the NH_4NO_3 treatments since exchangeable Al values were much higher and the amount of exposed bare ground was higher with this treatment (as a result of Al toxicity). One confounding effect on total Al was the presence of large numbers of moles in the plots, which may have led to higher erosion rates than usual for grassed plots.

Tall Fescue Yields and Nutrient Uptake

Forage Yields

The average cumulative tall fescue yields are plotted as a function of fertilizer type in Fig. 9. The average yields were higher for alum-treated litter than with normal litter or ammonium nitrate. By the end of Year 8, the average cumulative yields from the plots fertilized with alum-treated litter were 58.9 Mg ha^{-1}, which was 6% higher than the yields with normal litter (55.4 Mg ha^{-1}) and 16% higher than the yields with NH_4NO_3 (49.3 Mg ha^{-1}). Cumulative yields from the unfertilized control plots were 23.1 Mg ha^{-1} for the 8-yr period.

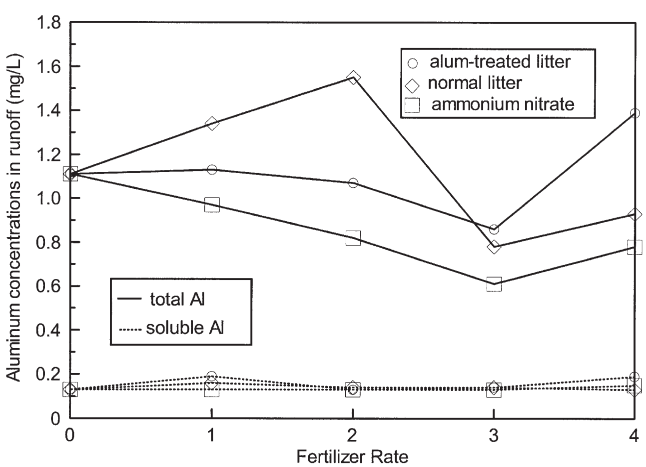

Fig. 8. Soluble and total Al concentrations in runoff at Year 6 as a function of fertilizer rate.

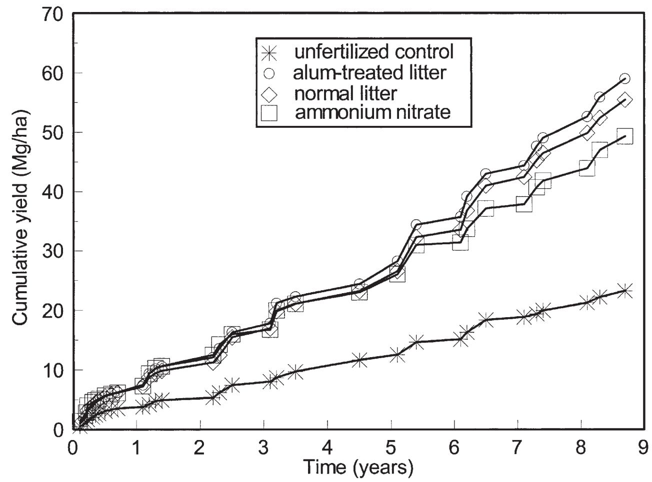

Fig. 9. Cumulative tall fescue yields as a function of time for the various fertilizer types. Data represent the average of four rates of each fertilizer source.

Cumulative tall fescue yields as a function of fertilizer rate are plotted in Fig. 10. Alum-treated litter resulted in the highest yield at all fertilizer rates. Both alum-treated and normal litter at the highest two rates resulted in significantly higher yields than NH_4NO_3 at the respective N rate. The only significant difference in cumulative yields between the two litter types was at the lowest litter rate (2.24 Mg ha^{-1}). At this rate, the yields from alum-treated litter were 41.3 Mg ha^{-1} versus 32.6 Mg ha^{-1} for the plots fertilized with normal litter (27% difference). These data indicate that alum-treated litter is the most sustainable fertilizer source of the three studied.

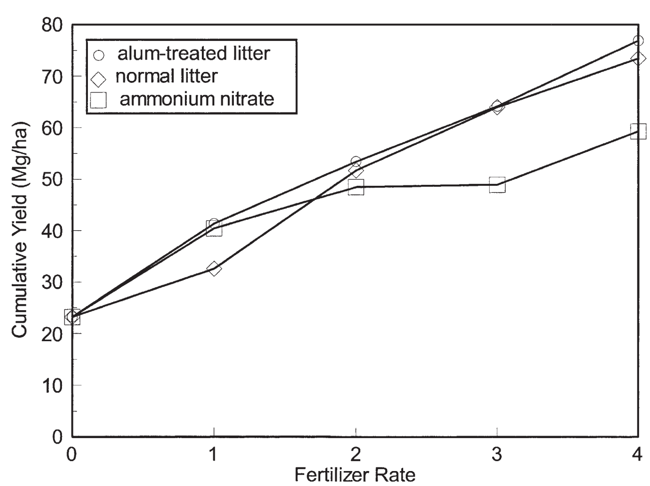

Fig. 10. Cumulative tall fescue yields as a function of fertilizer rates after 8.7 yr ($LSD_{0.05}$ = 9.2). Fertilizer rates (Rates 1, 2, 3, and 4) were respectively 2.24, 4.49, 6.73, and 8.98 Mg ha^{-1} for poultry litter and 65, 130, 195, and 260 kg N ha^{-1} for ammonium nitrate.

Table 2. Forage Al contents as a function of time and treatment.

		Alum-treated litter (Mg ha^{-1}) treatment				Normal litter (Mg ha^{-1}) treatment				NH_4NO_3 (kg N ha^{-1}) treatment				
Date	Control	2.24	4.49	6.73	8.98	2.24	4.49	6.73	8.98	65	130	195	260	$LSD_{0.05}$
	mg Al kg^{-1}													
25 Sept. 2001	49.3ab†	40.8abc	34.9bc	39.3abc	28.2c	36.9bc	37.3abc	37.9abc	30.0c	37.1bc	40.8abc	42.3abc	52.8a	15.6
3 May 2002	64.7a	49.1bc	44.3bc	46.8bc	59.0ab	46.9bc	34.2c	40.9c	49.3bc	48.4bc	43.0c	49.3bc	69.1a	15.4
18 June 2002	20.4a	14.4bcd	15.5bc	12.4bcd	10.6d	17.0ab	13.8bcd	11.7cd	11.4cd	13.6bcd	13.8bcd	13.4bcd	14.6bcd	4.63
19 Aug. 2002	37.7ab	28.7abc	28.2abc	25.3bc	29.4abc	26.4abc	24.0bc	24.1bc	18.5c	24.6bc	31.3abc	42.5a	27.1abc	16.4
2 July 2003	36.3a	30.2abc	22.6cd	19.3d	24.5bcd	26.3bcd	20.4d	23.8bcd	21.5cd	23.7bcd	23.1cd	33.0ab	27.3abcd	9.35

† Means followed by the same letter for each date are not significantly different at the 0.05 probability level.

Aluminum Uptake

Aluminum concentrations in tall fescue varied from 10 to 69 mg Al kg^{-1} (Table 2). There were very few significant differences in plant Al concentrations, although the two highest rates of NH_4NO_3 and the unfertilized control plants tended to have the highest values. This was somewhat surprising since the NH_4NO_3 treatment resulted in such high levels of exchangeable Al and low pH values (i.e., we had hypothesized that plants grown with NH_4NO_3 would have much higher Al levels at all the rates studied). One possible explanation is as follows. In spring of 2001 (beginning of Year 6) a large amount of the tall fescue died in many of the NH_4NO_3 plots. Within a year volunteer bermudagrass [*Cynodon dactylon* (L.) Pers.] had encroached into the plots in areas where the tall fescue had died. We hypothesize that the bermudagrass must be less susceptible to Al toxicity than tall fescue and may use an Al exclusion mechanism (possibly at the root surface or within the roots) that prevents Al accumulation in the leaves and stems.

Forage samples used in this study were, for the most part, taken with a bagger mower. While this procedure is okay for almost every other element of interest, it results in severe Al contamination of plant tissue. Typical soils contain 7% Al (70 mg g^{-1}) and tall fescue normally contains less than 70 mg Al kg^{-1}. Hence, if the plant material gets as little as 1 g soil kg^{-1} plant, then the Al value obtained will be double the expected value. Unfortunately, many of the plots used in this study had a high density of moles, which made burrows near the soil surface. When the plots were harvested with a bagger mower, soil contamination occurred, thus these data are not presented. The plant Al data shown in Table 2 were from plants harvested by hand with clippers to avoid soil contamination.

CONCLUSIONS

Results from long-term small plot trials showed that both normal poultry litter and alum-treated litter increased soil pH compared to the unfertilized control plots, whereas NH_4NO_3 applied at the same N rates as alum-treated litter greatly reduced soil pH. Aluminum availability was not affected by alum-treated or normal poultry litter applications; however, plots fertilized with NH_4NO_3 had elevated levels of exchangeable Al after Year 3, which was caused by low soil pH. Aluminum runoff and plant Al levels were not affected by any of the treatments. Cumulative tall fescue yields were 6% higher with alum-treated litter than normal litter, which was believed to be due to a higher N content of alum-treated litter as a result of lower NH_3 volatilization losses. The lowest tall fescue yields were found with NH_4NO_3 and were 16% lower than yields from alum-treated litter.

Previous studies have shown that the addition of alum to poultry litter reduces P, heavy metal (As, Cu, and Zn), and hormone runoff. Alum additions have also been shown to greatly reduce NH_3 emissions to the atmosphere, which would decrease aquatic N loading. The data shown in this study indicate that alum use does not negatively affect Al availability in soils, Al runoff, and/or Al uptake by plants. In fact, the use of alum caused yields to be consistently higher than the other fertilizers indicating that alum-treated litter is a more sustainable fertilizer than NH_4NO_3 and/or normal poultry litter.

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